

Assimilation of AIRS CO₂ Observations with EnKF in a Carbon-Climate Model

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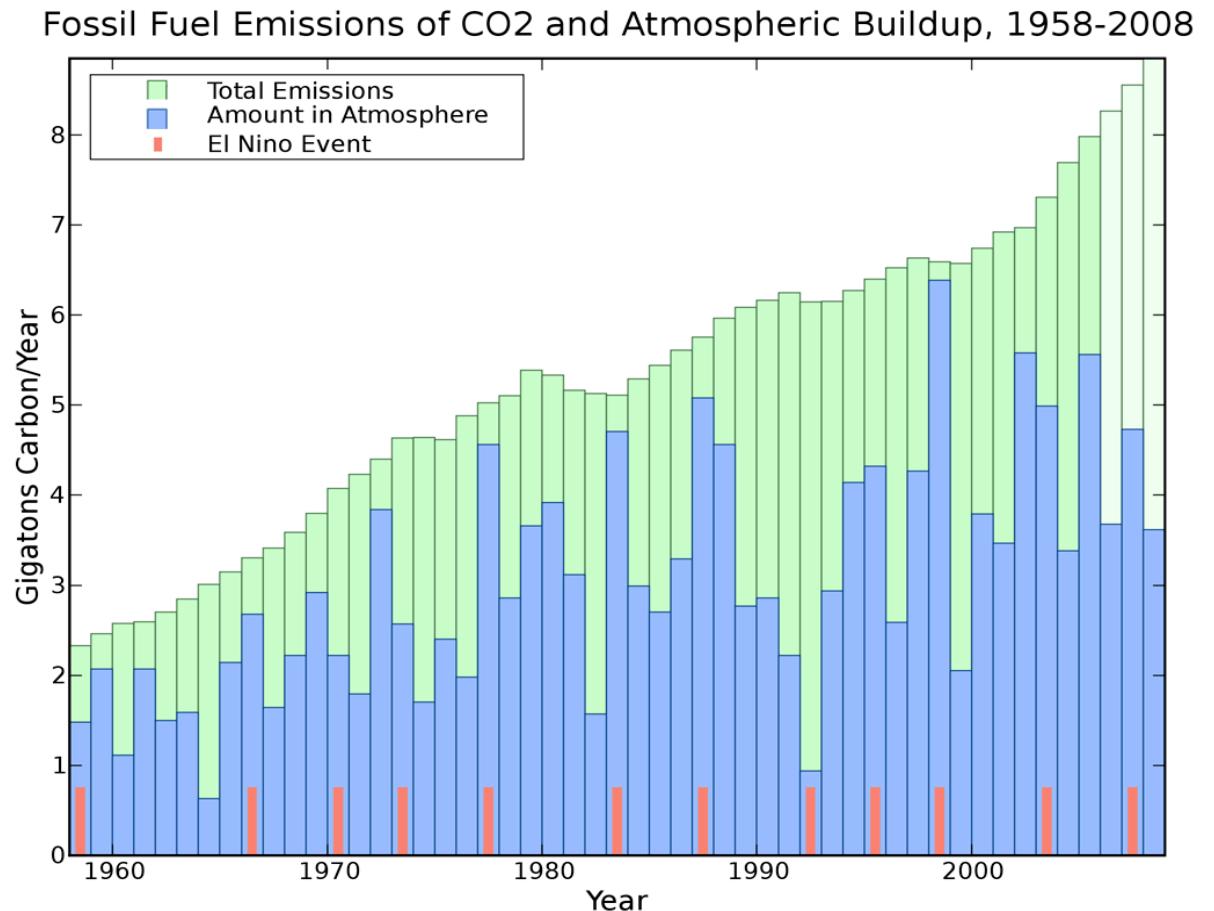
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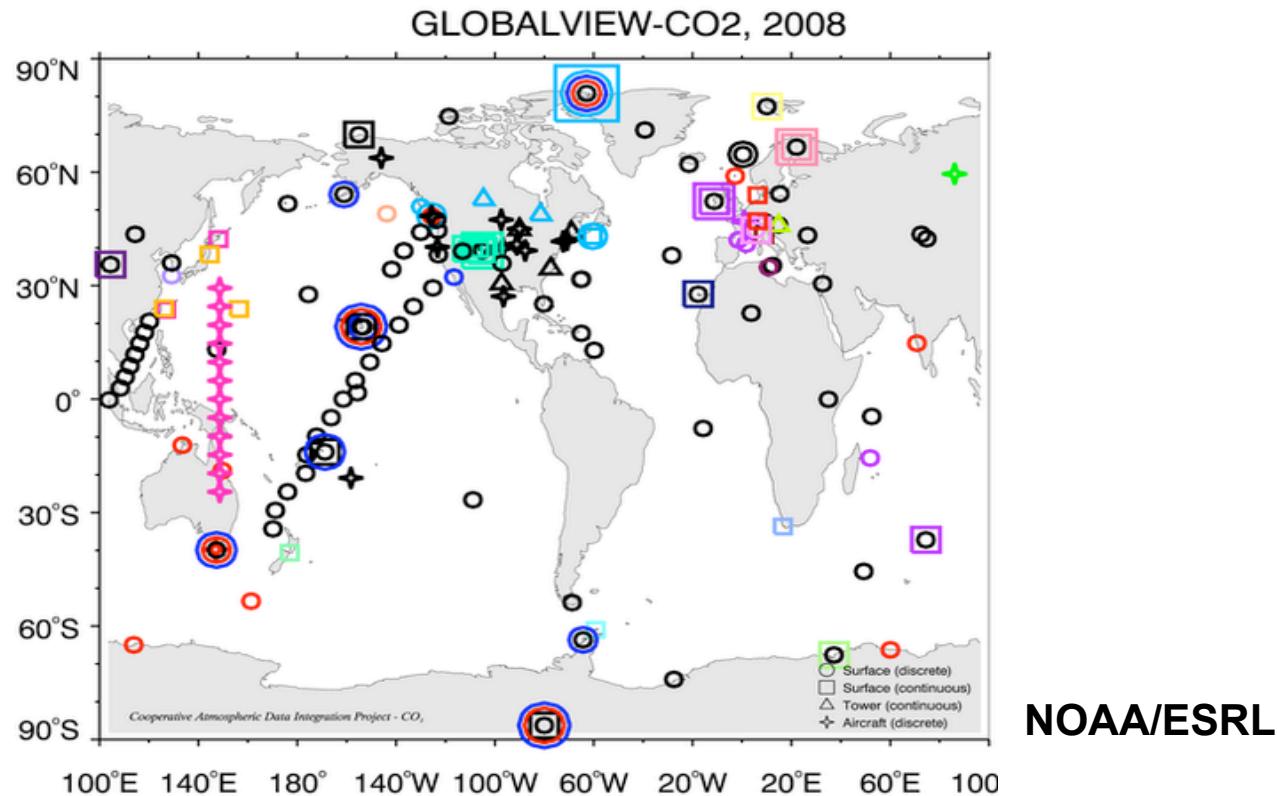
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Big Problem: The Elusive Carbon Sink

- Only half of the CO₂ produced by human activities is remaining in the atmosphere.
- Where are the sinks that are absorbing about 50% of the CO₂ that we emit?
 - Land or ocean?
 - Eurasia/North America?
- How will CO₂ sinks respond to climate change?



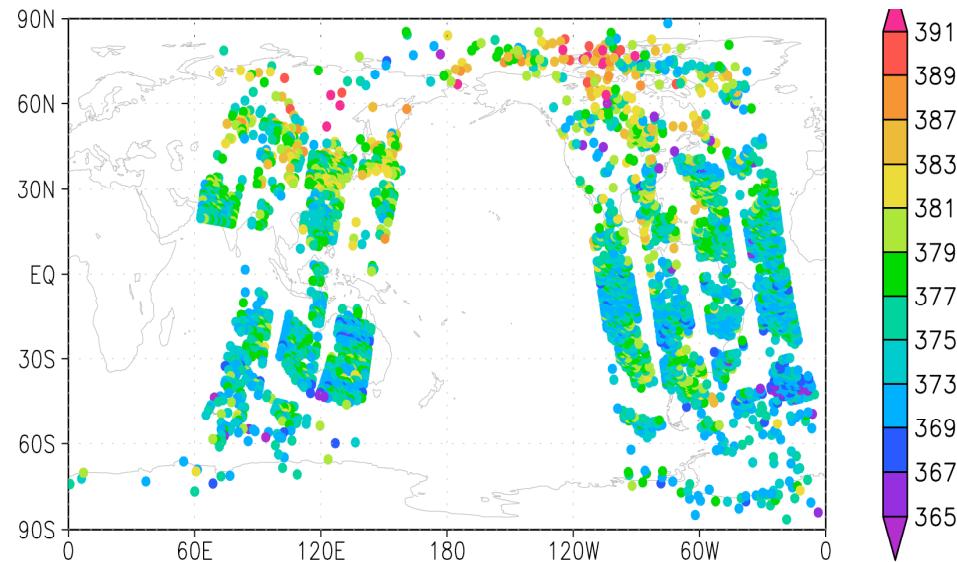
Background: Top-down Approach & Conventional CO₂ Observation Coverage



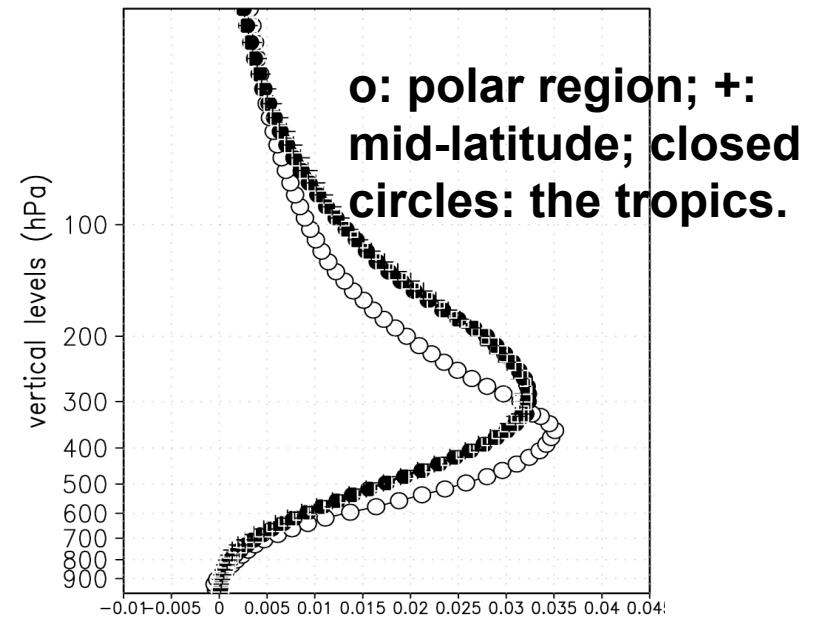
- Top-down approach: CO₂ concentrations->carbon flux
- Carbon flux estimation has been constrained by limited observation coverage.

AIRS CO₂ Observations & Research Goals

AIRS CO₂ at 18Z01May2003 (+/-3hour)

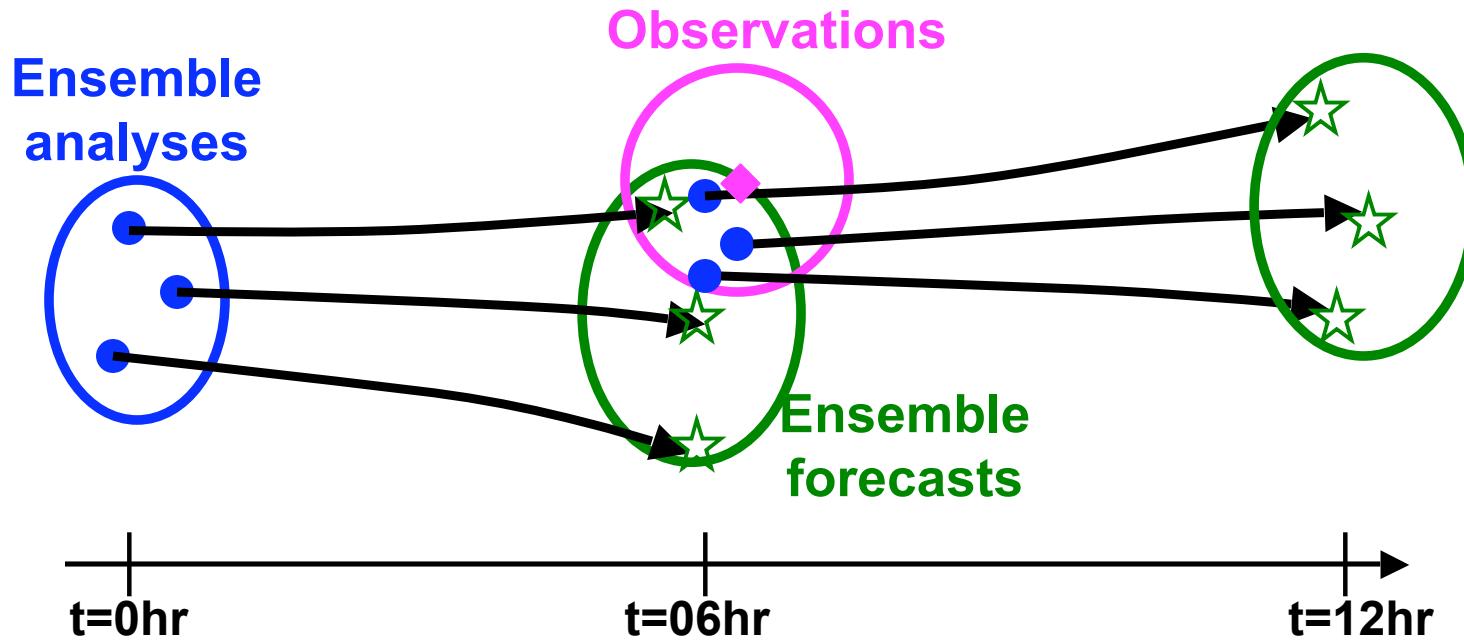


AIRS averaging kernel



- Generate CO₂ vertical profiles
- Preliminary results on surface carbon flux estimation.

Ensemble Kalman Filter process



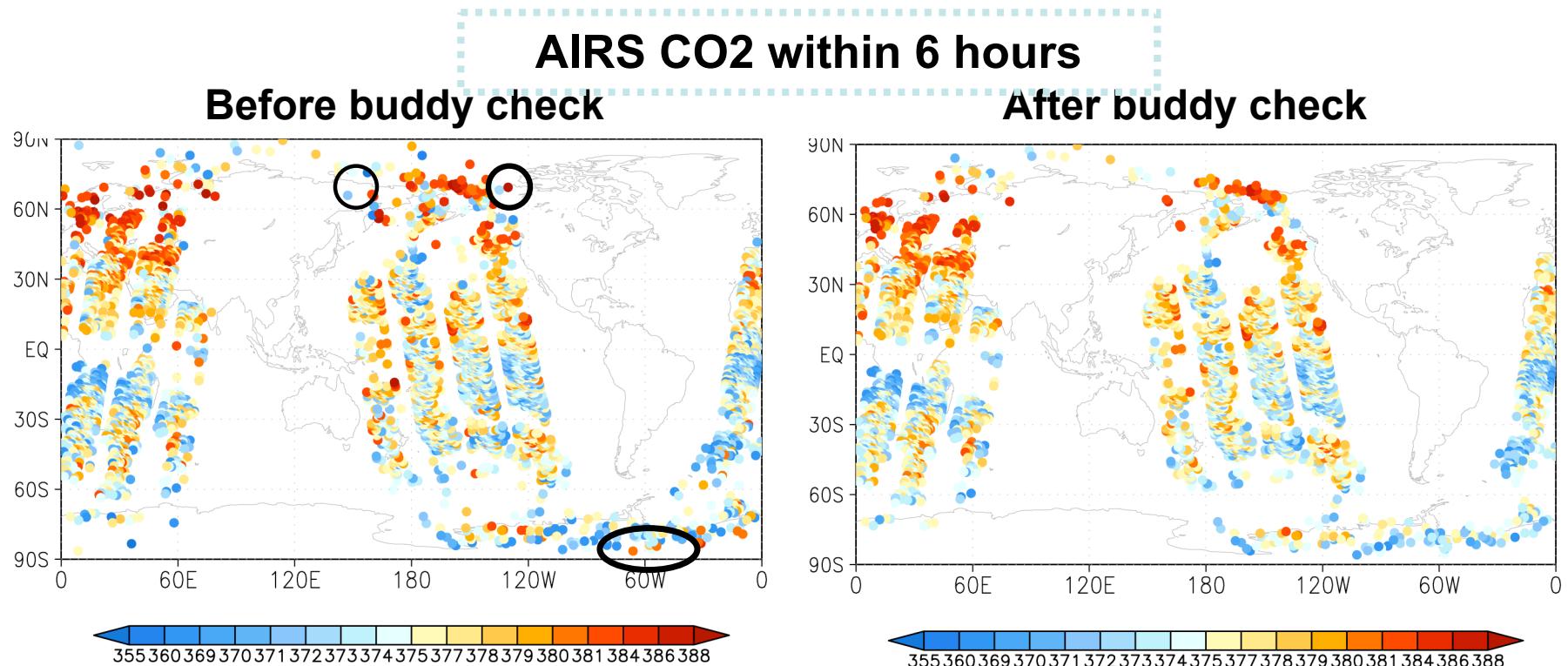
- Blue: analysis ensemble and its uncertainty; Green: background ensemble and its uncertainty; Magenta: observation and its uncertainty; Background error changes with time;
- Obtain ensemble analyses;

Carbon-Climate Model

- Community Atmospheric Model 3.5 (CAM 3.5) coupled with Community Land Model 3.5 (CLM 3.5)
 - Finite Volume dynamical core
 - $2.5^\circ \times 1.9^\circ$ horizontal resolution, with 26 vertical levels up to 3.5hPa.
- CO₂ is transported as a tracer in CAM 3.5
- Carbon surface fluxes:
 - Fossil fuel emission (yearly average value for 2003)
 - Ocean C fluxes (monthly means, interpolated between months; Takahashi et al., 2002)
 - Land C flux (6-hourly carbon flux from CASA)
- Initial CO₂ is the spin-up after 3 years.
- Assimilation time period: 01Jan2003-30June2003

Quality Control: Buddy Check

Buddy check: compare each obs to the mean of the adjacent obs



The quality of the rejected obs is not necessarily bad by itself!

- **8% of AIRS CO₂ observations were deleted in this way**

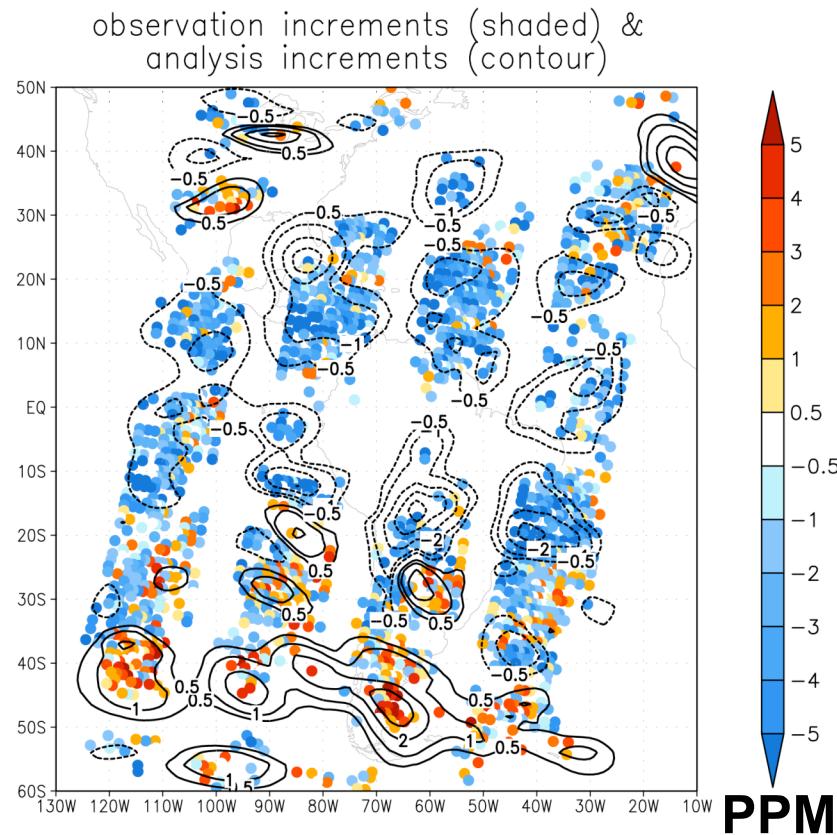
CO₂ Observation Operator

- Model forecast x^b is CO₂ vertical profile;
- AIRS CO₂ is column-weighted Volume Mixing Ratio (vmr);
- => **observation operator**: interpolate x^b to obs location & calculate model forecast column-weighted CO₂ vmr.

$$\underbrace{y^b}_{\text{model forecast "obs"}} = \underbrace{\mathbf{A}^T}_{\text{avg kernel}} \underbrace{(\mathbf{S})}_{\text{spatial interpolator}} (\underbrace{\mathbf{x}^b}_{\text{model forecast}})$$

obs operator

Analysis Increments (contour) & Observation Increments (shaded) At One Assimilation Cycle



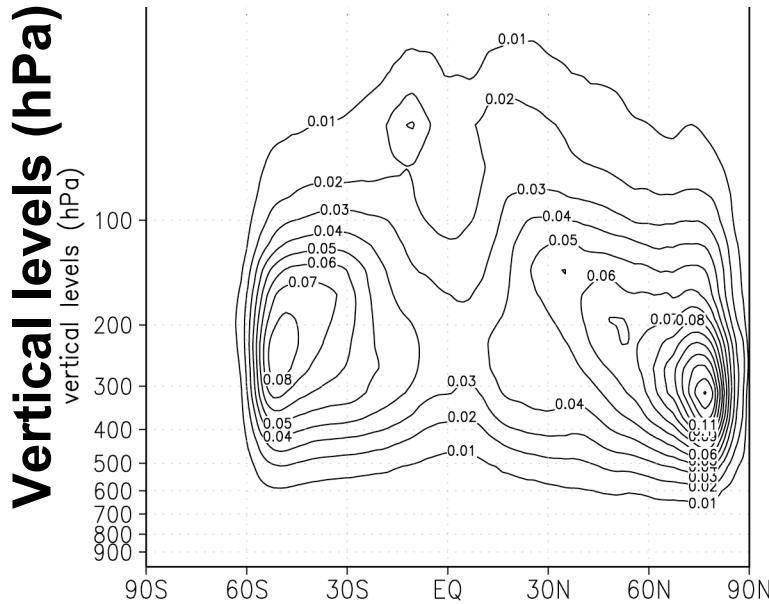
Analysis increments: the difference between analysis and forecast;

Observation increments: the difference between observation and forecast

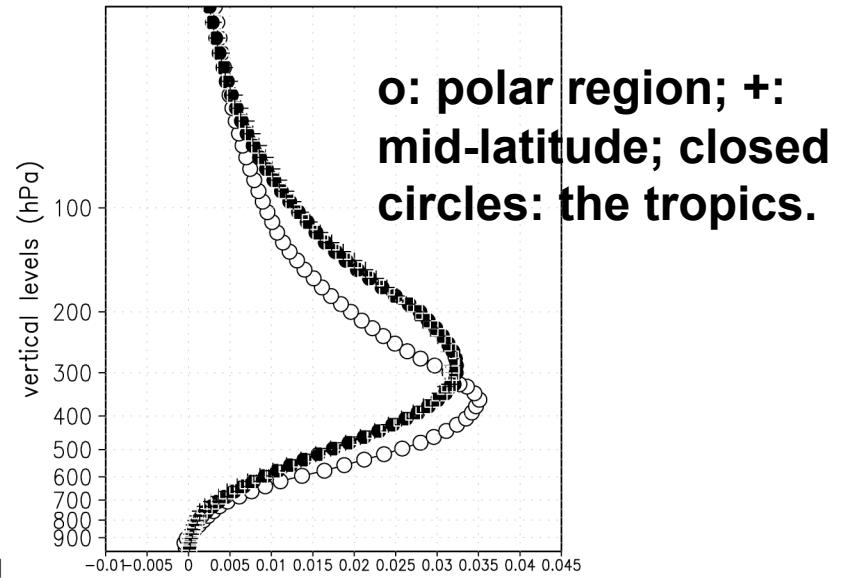
- Analysis increments agree with observation increments

Time-averaged Absolute Analysis Increments

Time-averaged absolute analysis increments

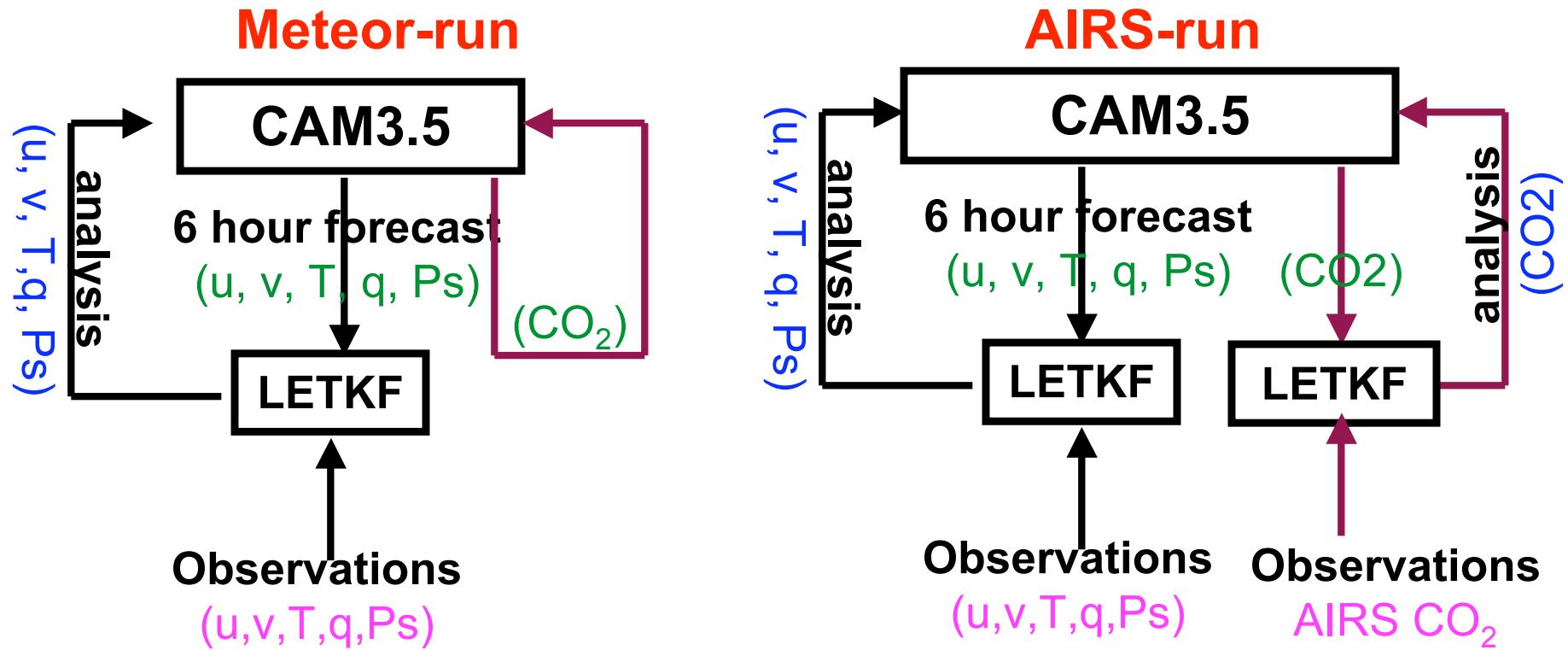


Averaging Kernel



- Obtain CO₂ vertical profiles from column weighted CO₂; no AIRS CO₂ observations beyond 60°S.
- Analysis increments peak at the similar levels of the peak of the averaging kernels.

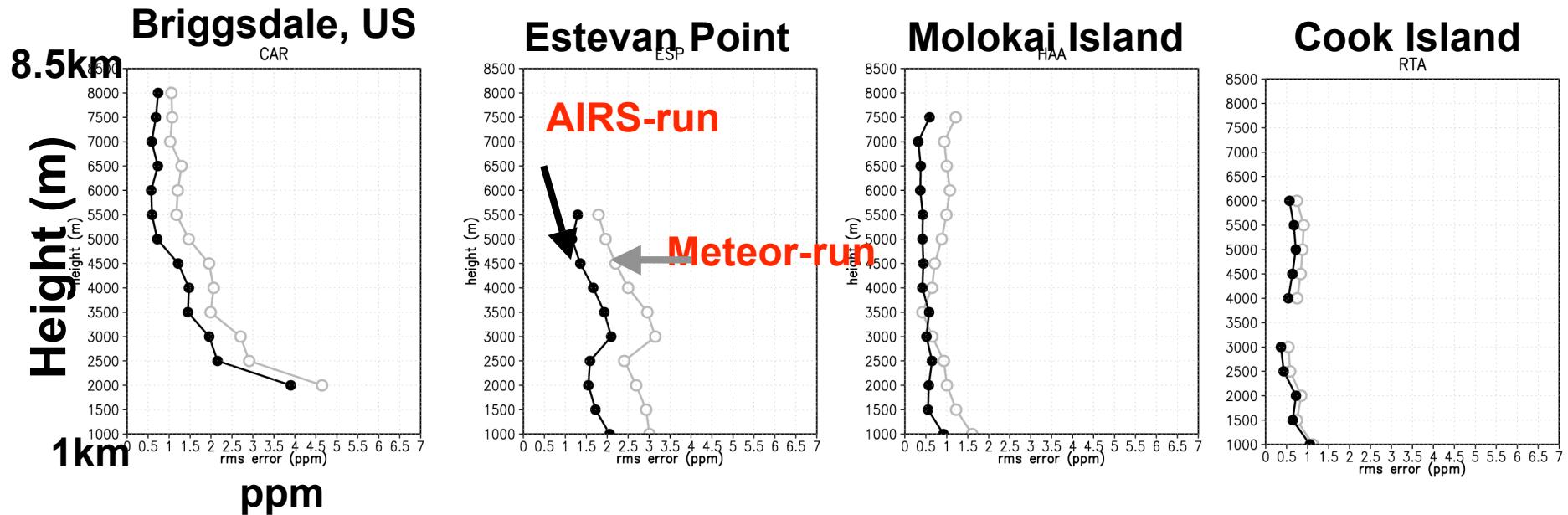
The Impact of AIRS CO₂ Assimilation



LETKF: Local Ensemble Transform Kalman Filter (Hunt et al., 2007)

- Assimilate meteorological observations along with AIRS CO₂

Verified Against Independent Aircraft CO₂

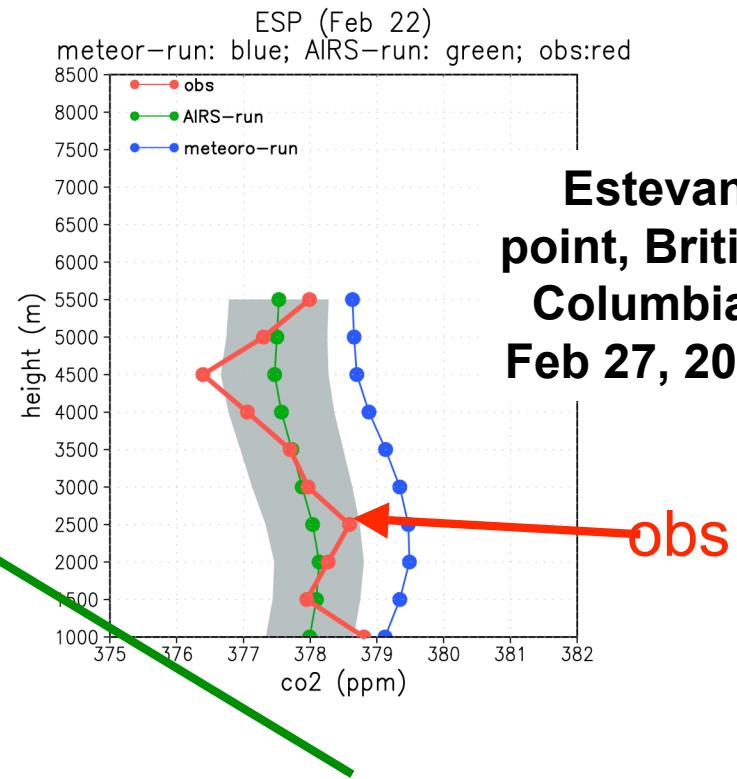
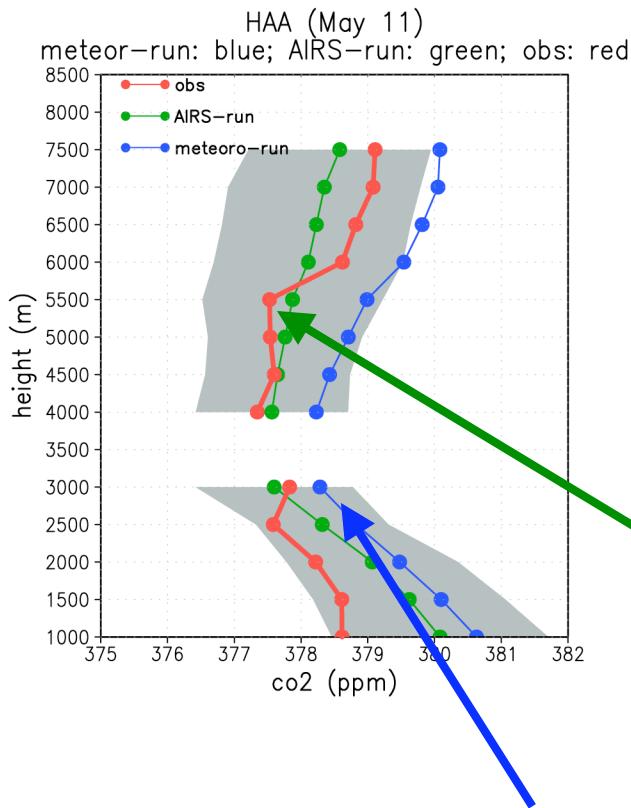


Time average of all the cases between 01Jan2003-30June2003

- Grey: meteor-run; black: AIRS-run.
- CO₂ vertical profiles from the AIRS-run can be about 1 ppm more accurate than those from the meteor-run.

Analysis ensemble spread along with the mean state

Molokai
Island,
Hawaii.
May 11,
2003

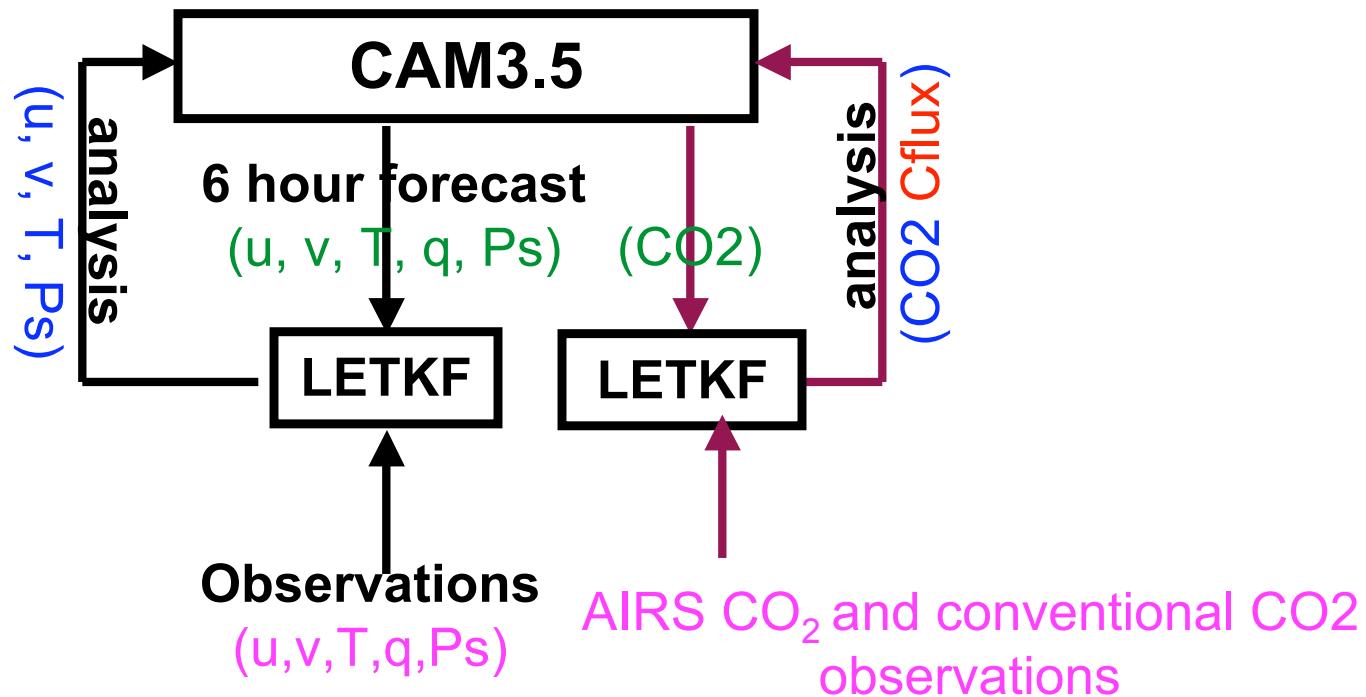


Estevan
point, British
Columbia,
Feb 27, 2003

- Meteor-run: CO₂ tracer transported by 64-member ensemble meteorological analyses generated every 6hr
- Ensemble CO₂ analyses (grey shaded) bracket aircraft obs
- AIRS-run: CO₂ assimilated along with meteorological obs.

Preliminary results on surface carbon flux estimation by assimilating AIRS CO₂

The impact of AIRS CO₂ assimilation

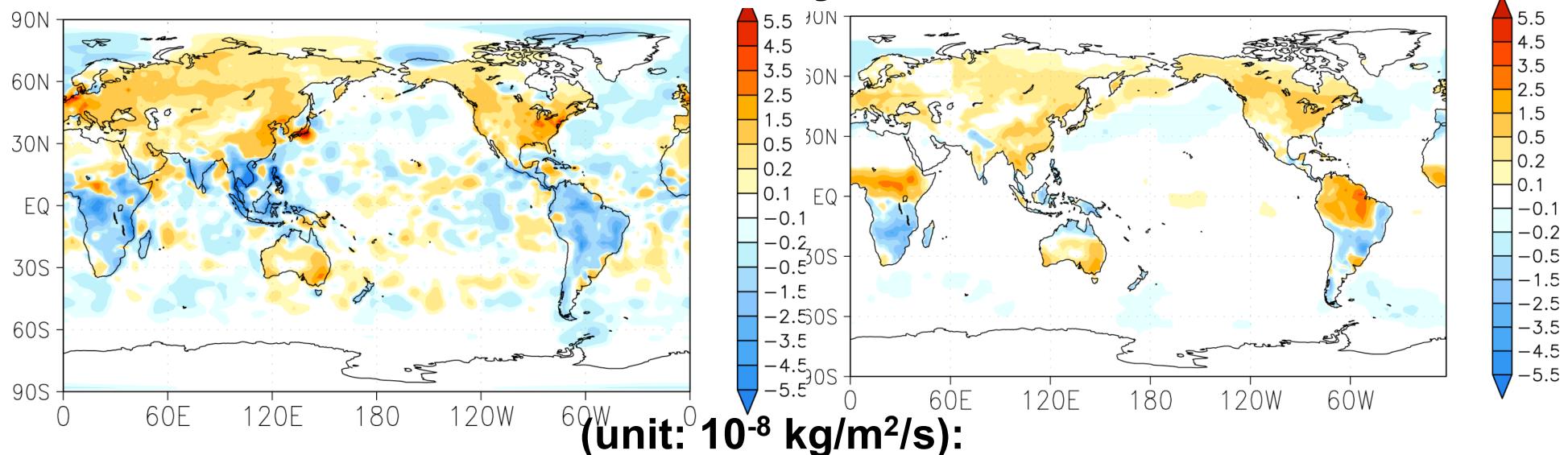


LETKF: Local Ensemble Transform Kalman Filter (Hunt et al., 2007)

- The carbon flux analysis acts as boundary forcing for the forecast of next time step.
- Three-month assimilation cycles (01Jan2003-31March2003).

Carbon Flux Analysis: Data Assim (left) Carbon Flux (CASA (land)+Takahashi (ocean))(right)

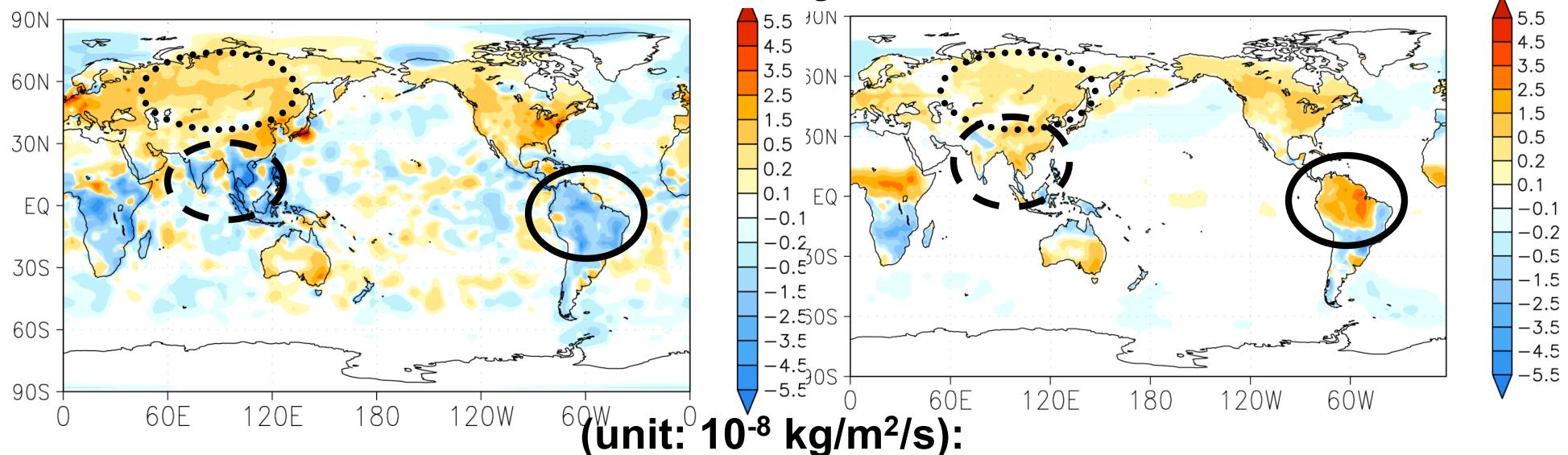
February 2003



- Stronger source in the NH winter
- Stronger sink in the tropics and SH subtropics
- Noisy over ocean compared to Takahashi

Carbon Flux Analysis: AIRS CO₂ Data Assim (left) Carbon Flux (CASA (land)+Takahashi (ocean))(right)

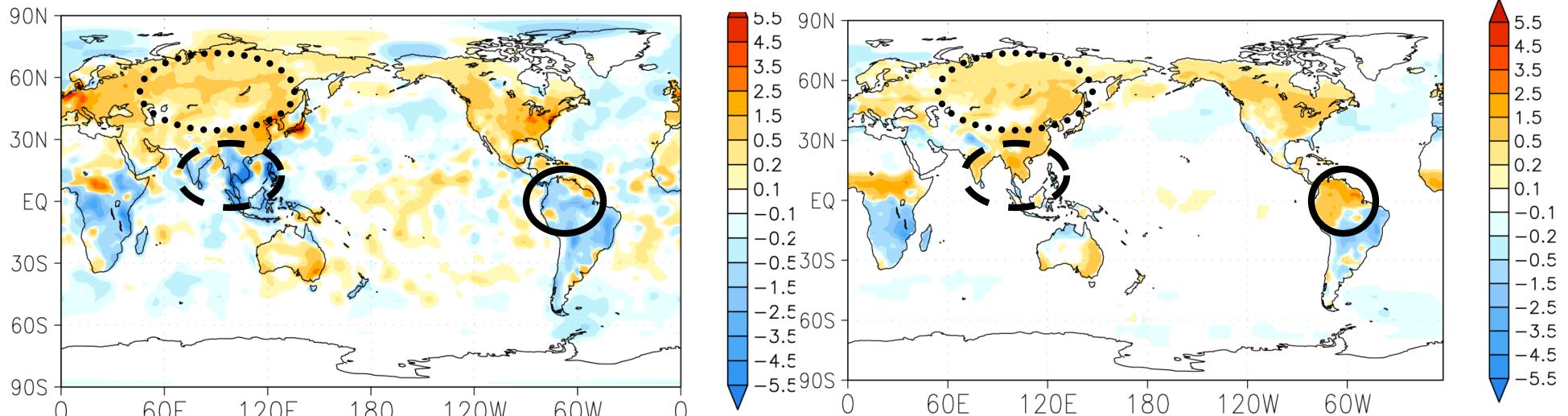
February 2003



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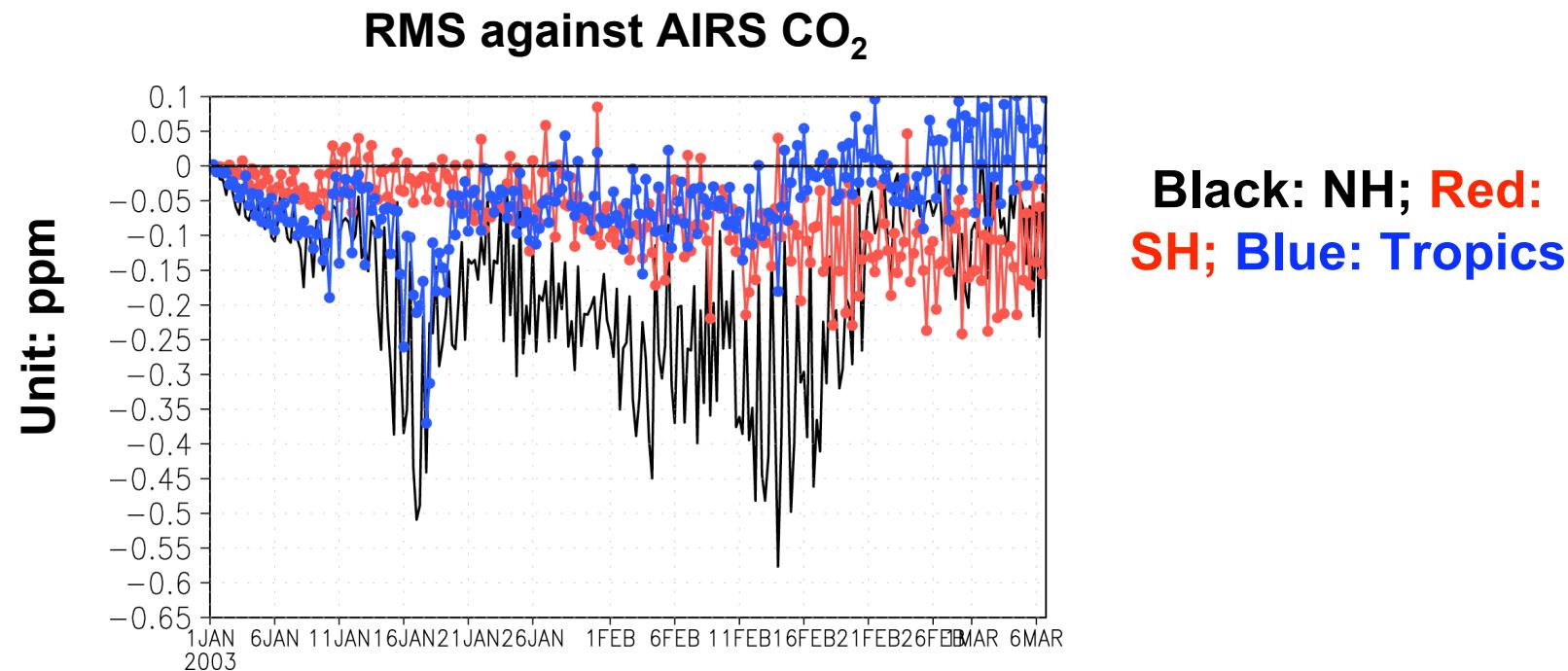
Carbon flux analysis (left) and carbon flux (CASA+Takahashi)(right) (unit: 10^{-8} kg/m²/s): Mar

March 2003



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RMSE Difference Between CO₂ Analyses From Carbon Flux Analysis and those from Fixed Carbon Flux



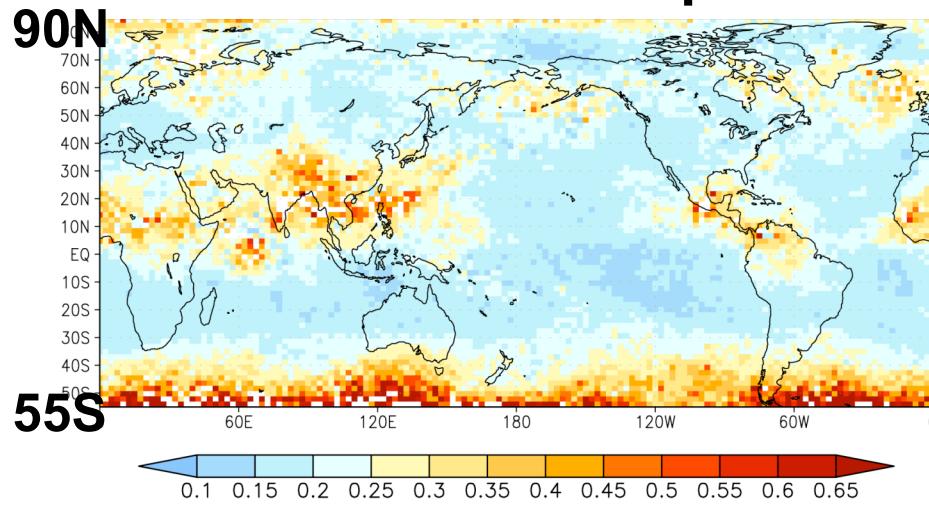
- Negative: carbon flux analysis is more accurate than fixed carbon flux when verified against AIRS CO₂.
- Stronger fluxes drive CO₂ to better agreement with AIRS CO₂!

Summary and Future Directions

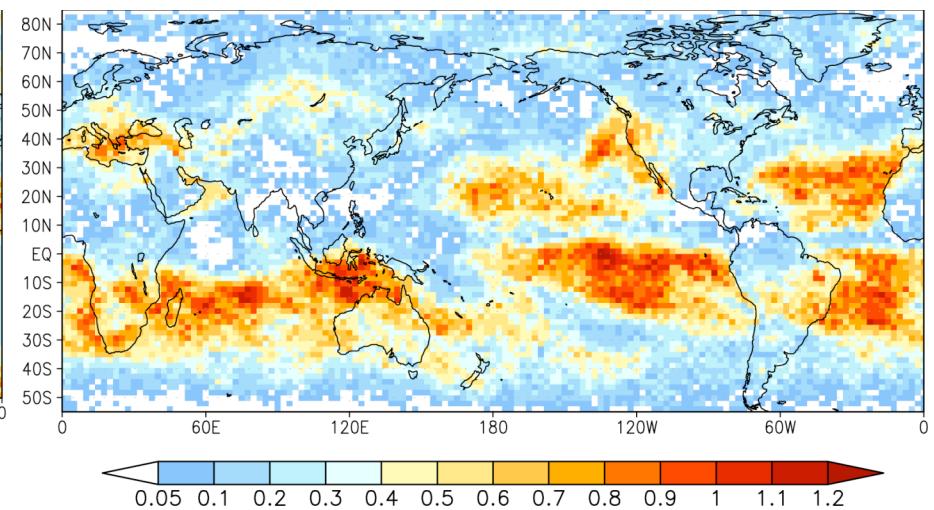
- Assimilation of CO₂ observations have improved the CO₂ vertical profiles;
 - The ensemble analyses encompasses the aircraft CO₂ vertical profiles.
 - The preliminary surface carbon flux estimation from assimilating AIRS CO₂ and conventional CO₂ observations are encouraging!
- ✓ Extend surface carbon flux estimation, and seek more solid validation of carbon flux analysis.

Relationship Between Analysis Ensemble Spread and Observation Coverage

CO_2 analysis ensemble spread at observation space



Average number of AIRS CO_2 observations within 6-hour



- Analysis ensemble spread is anti-correlated with the the CO_2 observation coverage